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TEST FOR EXOTIC ISOSCALAR RESONANCE DOMINATING $D^0 \to \pi^+\pi^-\pi^0$ DECAYS

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The decay $D^0 \to \pi^+\pi^-\pi^0$ appears to be dominated by $\rho\pi$ states in a configuration of zero total isotopic spin. The spin J, parity P, and charge-conjugation eigenvalue C of this final state are therefore $J^{PC} = 0^{--}$, which cannot be formed of a quark q and antiquark $\bar{q}$. If a resonance near $M(D^0)$ dominates the final state, it must be a *hybrid* composed of a quark-antiquark pair and a constituent gluon, or a *tetraquark* $qq\bar{q}\bar{q}$. A test for this resonance in electroproduction is proposed.

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I INTRODUCTION

The decay of the charmed meson D^0 into $\pi^+\pi^-\pi^0$ exhibits a curious dominance by the state of zero total isotopic spin [1, 2]. Since this three-pion state has odd G-parity and $I = 0$, its charge-conjugation eigenvalue C is negative. Since it is a three-pion state in a state of zero total angular momentum J, its parity P is also negative. It thus has $J^{PC} = 0^{--}$, a CP-even configuration which cannot be formed of a quark and antiquark. The even CP property has been confirmed by subsequent analyses [3, 4]. The latest finds the three-pion state to have $CP = +$ $(97.3 \pm 1.7)\%$ of the time, which includes a small (few-%) contribution from $I = 2$ [5]. This observation has a useful implication for the determination of the CP-violating CKM (Cabibbo-Kobayashi-Maskawa) phase γ in decays of the class $B^{\pm,0} \to D_{\rm CP} K^{(*)\pm,0}$ [6, 7].

The dominance of $I = 0$ can be reproduced [5] in flavor-SU(3) analyses of all PV decays of charmed mesons, where P and V stand for light pseudoscalar and vector mesons. Topological amplitudes T ("color-favored tree"), C ("color-suppressed tree"), and E ("exchange") cooperate in such a way as to give $I = 0$ intensity fractions of $(92.9 \pm 6.7)\%$ in the fit of Ref. [8] and $(90.9 \pm 18.2)\%$ in the fit of Ref. [9]. The possibility of dominance by a non-$q\bar{q}$ resonance near $M(D^0) \simeq 1865$ MeV was mentioned in Refs. [2, 5]. In the present work we propose a means of testing this hypothesis.

This paper is organized as follows. In Section II we review some properties of resonances in charm decays and of a new hybrid state near M_D. We then stress the need for electroproduction of a spinless resonance via pion exchange in Sec. III. Possible interpretations of a signal are described in Sec. IV. A detailed program for anticipating signal strength is set forth in Sec. V, while possible variants to this approach are noted in Sec. VI. Sec. VII summarizes. An Appendix examines assumed relations among photoproduction of light mesons.

II RESONANCES IN CHARM DECAYS

The role of nearby resonance states in charmed meson decays has been pointed out a long time ago [10]. Dominant contributions to $D^0 \to K^-\pi^+$ of strangeness minus one $q\bar{q}$ resonances with masses below and near the D^0 mass have been studied in Ref. [11]. It was also argued in Ref. [9] that an intermediate glueball state at $f_0(1710)$ could explain the large ratio $\Gamma(D^0 \to K^+K^-)/\Gamma(D^0 \to \pi^+\pi^-)$.

We denote the proposed resonance by $X(0^{--})$, where the quantity in parentheses refers to J^{PC}. The Dalitz plot for $D^0 \to \pi^+\pi^-\pi^0$ appears to be dominated by three $\rho\pi$ bands of approximately equal strength; they would be strictly equal in the $I = 0$ limit.

A contribution of a given resonance R to D^0 decay into a final state f is given by

$$A_R(D^0 \to f) = \frac{\langle R|H_W|D^0\rangle g_{Rf}}{m_D^2 - m_R^2 - im_R\Gamma_R} \ , \tag{1}$$

where $\langle R|H_W|D^0\rangle$ is the weak Hamiltonian matrix element between D^0 and R states, g_{Rf} is the strong decay coupling of the resonance to f, while m_R and Γ_R are the resonance mass and width. We will now compare the two factors in the numerator and the Breit-Wigner denominator for $R = X, f = \rho\pi$ and $R = \bar{K}^{*0}, f = K^-\pi^+$.

It seems impossible to present a reliable model for calculating the strong coupling (or the width) of the hybrid meson $X(0^{--})$ to $\rho\pi$. No such attempt has been made in Refs. [12]–[18] studying hybrid states in QCD. This stands in contrast to the strong coupling of the strangeness minus one $q\bar{q}$ spin zero resonance $\bar{K}^{*0}(1430)$ to $K^-\pi^+$ which has been well measured through the resonance width [19]. The contribution of $\bar{K}^{*0}(1430)$, peaking 436 MeV below the D^0 mass, to the $D^0 \to K^-\pi^+$ amplitude has been calculated to be around 30% of this amplitude [11]. The latter paper also suggested that another $s\bar{d}$ P-wave resonance (most likely an $n = 2$ radial excitation) around 1900 MeV may dominate the amplitude.

It is difficult to compare quantitatively D^0 weak interaction matrix elements for final states $|X(1865)\rangle$ and $|\bar{K}^{*0}(1430)\rangle$ involving CKM factors $V_{cd}V^*_{ud}$ and $V_{cs}V^*_{ud}$. The respective quark transitions $c(\bar{u}) \to d\bar{u}d(\bar{u})$ and $c(\bar{u}) \to s\bar{u}d(\bar{u})$ involve two quark-antiquark pairs in the final state. This seems to favor a tetraquark state X in the first transition over a quark-antiquark state $\bar{K}^{*0}$ in the second transition.

Considering only the magnitudes of the two Breit-Wigner denominators for $D^0 \to X(1865) \to \rho\pi$ and $D^0 \to \bar{K}^{*0}(1430) \to K^-\pi^+$ one finds their ratio to be $2.08/(1.865\,\Gamma_X)$ [19], where Γ_X is given in GeV. For $\Gamma_X = 0.3$ GeV this by itself would favor by a factor 3.7 this resonant contribution to $D^0 \to \pi^+\pi^-\pi^0$ over the contribution of $\bar{K}^{*0}(1430)$ to $D^0 \to K^-\pi^+$, and thus favor essentially complete $X(1865)$ dominance of the former decay.

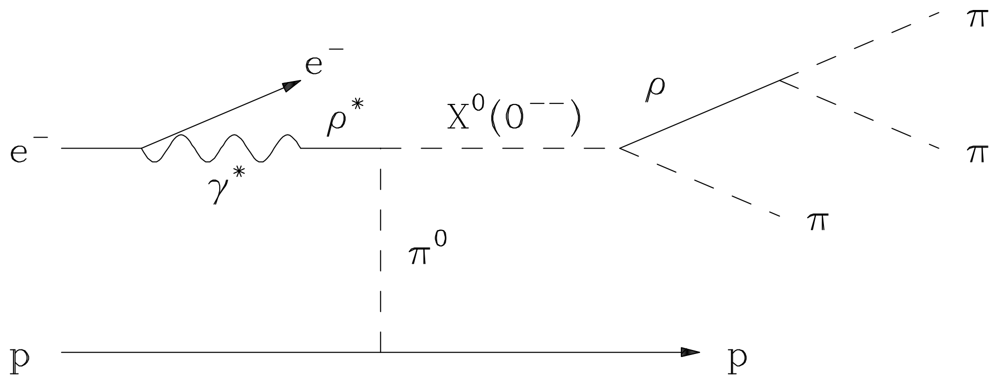

Figure 1: Electroproduction of a hypothetical $X(0^{--})$ resonance with mass near $M(D^0 \simeq$ 1865 MeV, observed through its decay to $\pi^+\pi^-\pi^0$.

III ELECTROPRODUCTION IN PION EXCHANGE

Based on the coupling of the resonance to $\rho^0\pi^0$, we propose to electroproduce it on a proton target via π^0 exchange, as illustrated in Fig. 1. Photoproduction of a spinless state off a nearly real pion target is a forbidden $0 \to 0$ electromagnetic transition. Hence the cross section should vanish as the squared momentum transfer q^2 goes to zero. This behavior is familiar from the two-photon reaction $e^+e^- \to e^+e^- f_1(1285)$ [20–22]. Here the excitation of the spin-1 f_1 by two real photons is forbidden by the Landau-Yang theorem [23,24], so at least one of the electrons must undergo significant recoil. Pion exchange is most effective at small momentum transfers [25, 26], so virtual photons of the highest possible energy have an advantage in producing a massive state.

There will be conventional $q\bar{q}$ resonances coupling to $\rho\pi$. At lower masses these include $a_1(1260)$ $(J = 1)$, $a_2(1320)$ $(J = 2)$, $\omega(1650)$ $(J = 1)$, and $\omega(1670)$ $(J = 3)$ [19]. However, the $X(0^{--})$ should have a distinctive signature. It should decay mainly to $\rho\pi$, populating each of the three $\rho\pi$ bands equally, with a characteristic null along all three symmetry axes of the Dalitz plot [27]. Furthermore, as mentioned, its production via pion exchange should be suppressed as the virtual photon becomes closer to the mass shell.

The minimum momentum transfer should be of order $-m_\pi^2$ or smaller to efficiently utilize the pion pole. As shown in Fig. 2 [19], photons of 6 GeV (the original energy at Jefferson National Laboratory [JLAB]) can achieve $|t_{\rm min}| = \mathcal{O}(m_\pi^2)$ when exciting $a_1(1260)$ or $a_2(1320)$, while at least $E_\gamma = 12$ GeV (the upgraded JLAB energy) is required to achieve sufficiently small $|t_{\rm min}|$ when exciting a state with mass $M(D^0)$. Tagged photons in the 4.8–5.4 GeV range have been used by the CLAS Collaboration at JLAB to photoproduce a_2 and $\pi(1670)$ [28], but no signal for a_1 was seen. Pion exchange seems to account satisfactorily for a_2 production in this experiment and others in the 4–7 GeV range. (See Fig. 3 of [29].) It is noted in Ref. [29] that the COMPASS experiment at CERN [30], using muons of energy 160–200 GeV, also is capable of photoproducing or electroproducing light-quark meson states.

Other production mechanisms besides electroproduction are possible. For example, the process $\pi^+p \to X(0^{--})\Delta^{++}$ can proceed through charged ρ exchange, leading to a final state $(\pi^+\pi^-\pi^0)(\pi^+p)$. Photoproduction of an $X(0^{--})$ can receive nonzero contributions

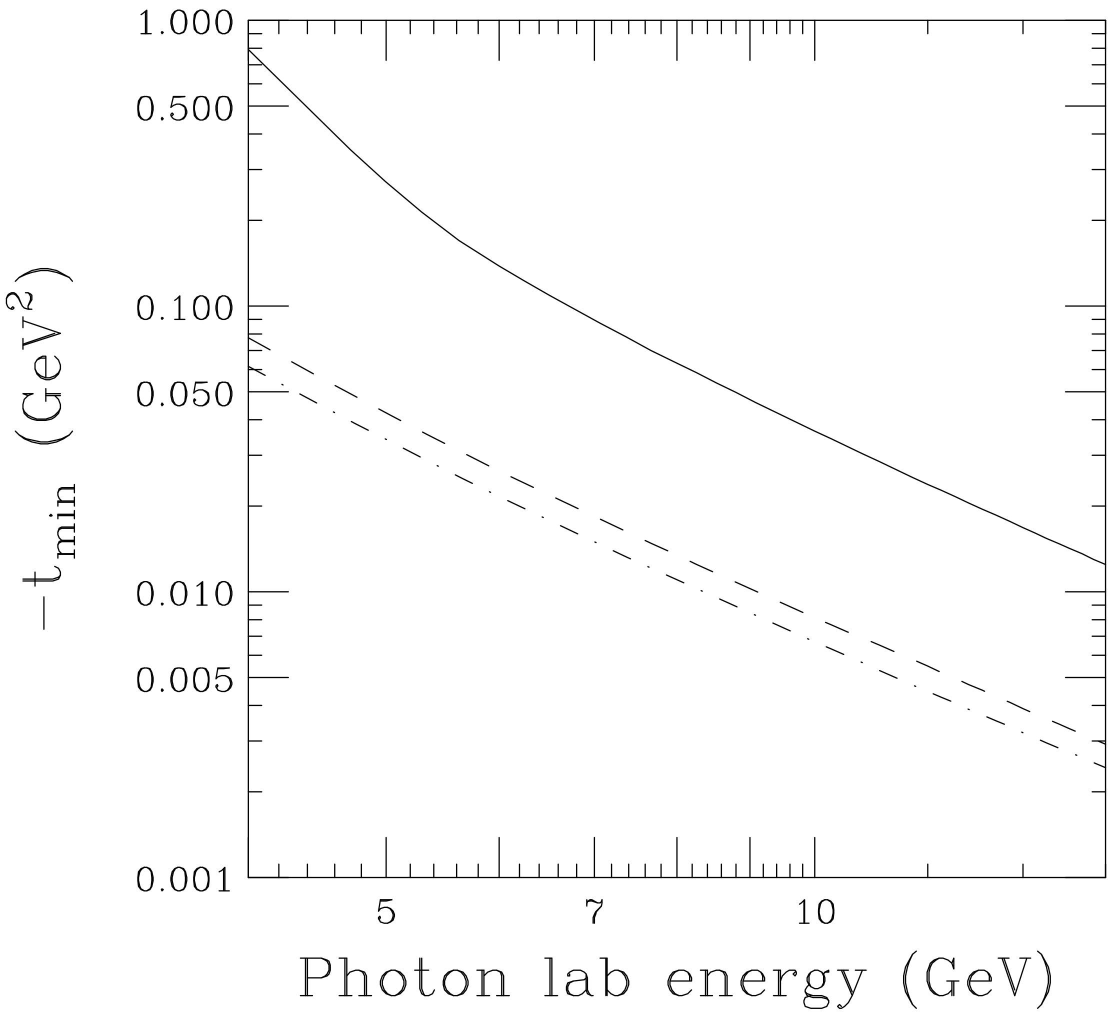

Figure 2: Values of $-t_{\min}$ for $\gamma p \to Xp$ as functions of incident photon laboratory energy E_γ. Solid line: $X = X(0^{--})$ [$M(X) = M(D^0 = 1865$ MeV]; dashed line: $X = a_2(1320)$; dot-dashed line: $X = a_1(1260)$. For large E_γ, $-t_{\min} \simeq M_X^4/(4E_\gamma^2)$. When the photon is virtual with $q^2 < 0$ this expression becomes $[(M_X^2 - q^2)/(2E_\gamma)]^2$.

from exchange of any neutral meson with $J \neq 0$ and $C = +$, such as the a_1 or a_2.

IV INTERPRETATION OF A SIGNAL

If the resonance is seen, it could be a hybrid or a tetraquark. A 0^{--} hybrid occurs in models involving constituent gluons [12–14]. In Ref. [13] it is expected in the mass range 1.8–2.2 GeV, so it could dominate D^0 decays. It is predicted to lie somewhat higher (2.3 GeV) in Ref. [14]. A gluon with $J^{PC} = 1^{--}$ can combine with a color-octet $I = 0$ $q\bar{q}$ state with $J^{PC} = 1^{++}$ (i.e., a ${}^3P_1$ state) in a state of relative orbital angular momentum zero to form the 0^{--} hybrid. Lower-mass hybrids in the range 1.3–2.1 GeV can be formed with a gluon and a color-octet ${}^1S_0$ or ${}^3S_1$ $q\bar{q}$ state, leading to hybrids with $J^{PC} = 1^{+-}$ and $(0,1,2)^{++}$, respectively. None of these is exotic. The lowest-lying exotic, with $J^{PC} = 1^{-+}$, is predicted in the constituent-gluon model to lie in the mass range 1.8–2.2 GeV, and to be composed of a gluon and a $q\bar{q}$ state with $J^{PC} = 1^{+-}$. Candidates for this state have shown up, typically at lower mass [12]. It is interesting that other models considered in Ref. [12] (bag [15], flux tube [16], lattice QCD [17], QCD spectral sum rules [18]) do *not* predict a 0^{--} state at comparable mass.

A tetraquark could serve as a proxy for a model with a consistuent gluon, by the simple subsitution of a color-octet, spin-1 $q\bar{q}$ $^3S_1$ pair in place of the gluon. Here there are more opportunities for forming a 0^{--} state with zero isospin, as both the $^3P_1$ and $^3S_1$ states can have either zero or unit isospin. (We are assuming only the two lightest quark flavors.)

V ANTICIPATING SIGNAL STRENGTH

The forthcoming GlueX experiment [31] is dedicated to searching for exotic states of matter in photon-proton collisions. However, the detector cannot be operated in an electroproduction mode, so production of the $X(0^{--})$ should be suppressed. GlueX *should* be able to photoproduce both $\omega(782)$ and its presumed radial excitation $\omega(1650)$, important steps (as we shall see below) toward electroproduction of the 0^{--} state. On the other hand, the CLAS12 detector [32] is designed to study resonance production with virtual as well as quasi-real photons, so it should be able to see the $X(0^{--})$, with cross section decreasing as $q^2 \to 0$. In the following we suggest experimental steps to see whether the required sensitivity can be achieved.

The electroproduction of a state whose production by real photons is forbidden requires one to know the relative flux of longitudinally and transversely polarized photons γ^* produced by a scattered electron:

$$e^-(k) \to \gamma^*(q) + e^-(k') , \tag{2}$$

where E and E' are the laboratory energies of the initial and final electron, $\nu \equiv E - E'$, and $Q^2 \equiv -q^2 = 4EE' \sin^2(\theta/2)$, where θ is the electron scattering angle in the laboratory. The cross section for $e^- + p \to e^- +$ (anything) can be decomposed into contributions from transversely and longitudinally polarized virtual photons [33]:

$$\frac{d^2\sigma}{d\Omega dE'} \propto \sigma_T + \epsilon\sigma_L \ , \quad \epsilon \equiv \left[1 + 2\left(\frac{\nu^2}{Q^2} + 1\right)\tan^2(\theta/2)\right]^{-1} . \tag{3}$$

One finds the following exact dependence of ϵ on E, E' and Q^2:

$$\epsilon = \frac{4EE' - Q^2}{2(E^2 + E'^2) + Q^2} . \tag{4}$$

Two examples of the behavior of ϵ and θ as functions of Q^2 are shown in Fig. 3 for $E = 12$ GeV and $E' = 1$ GeV (a,b) or $E' = 6$ GeV (c,d). For low values of Q^2 ϵ is very weakly dependent on this variable and is almost entirely a function of the ratio E'/E, $\epsilon \simeq 2(E'/E)/[1 + (E'/E)^2]$.

An amplitude for a process forbidden for real photons ($q^2 = 0$) will behave for $Q^2 \to 0$ as Q^2/M_0^2, where M_0 is some characteristic hadron mass. Taking it to be m_ρ, we may expect

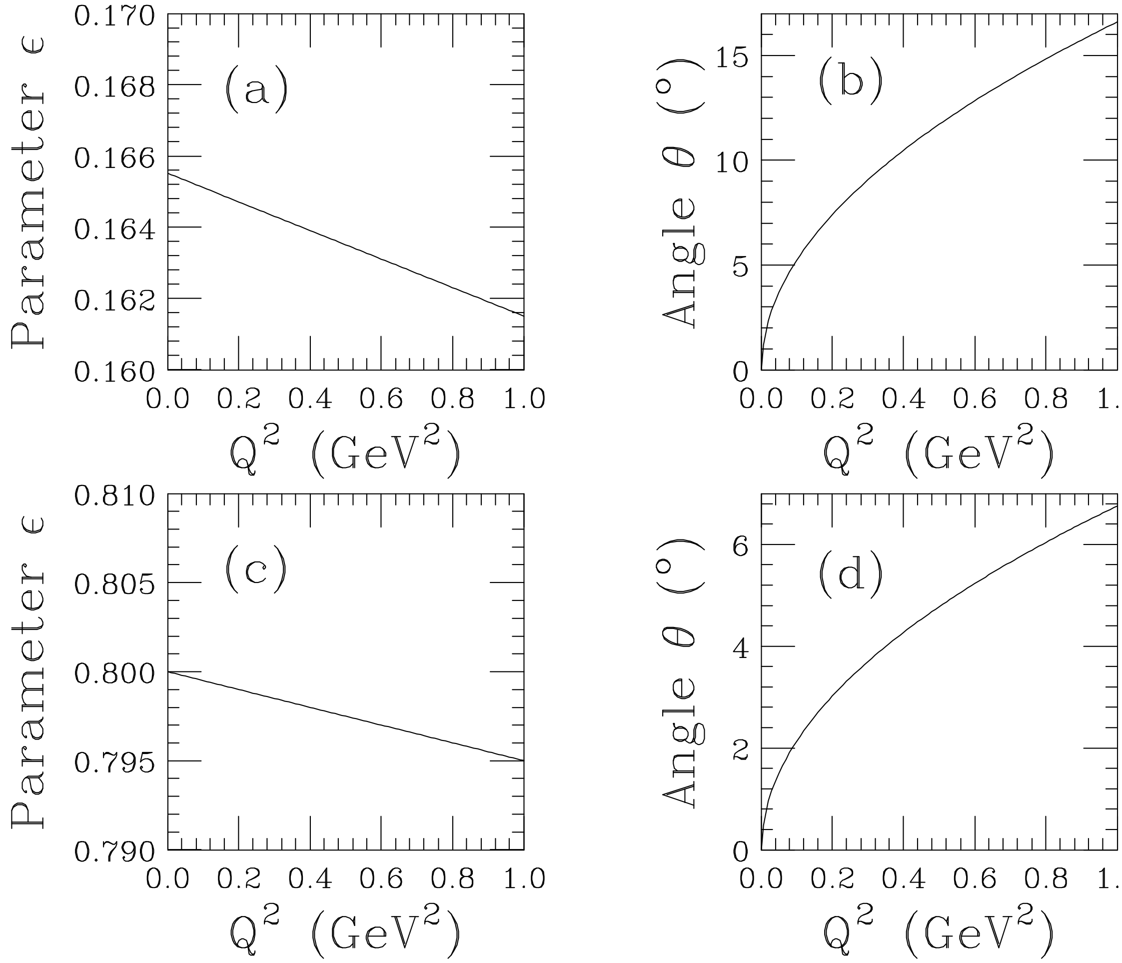

Figure 3: Behavior of virtual photon polarization parameter ϵ (a,c) and laboratory scattering angle θ (b,d) as functions of Q^2 for $E = 12$ GeV and $E' = 1$ GeV (a,b) or 6 GeV (c,d).

a suppression by about a factor of 2 relative to a typical photoproduction amplitude when $Q^2 \sim 0.3$ GeV^2. This is the maximum envisioned in one proposed CLAS12 experiment at JLAB [34].

If one wants the virtual photon to transfer as much energy ν as possible to the hadronic system, one wants E' to be not too large, as in Figs. 3(a,b). However, one pays the price of a smaller factor $\epsilon \simeq 2x/(1+x^2)$, where $x = E'/E$, which is about 1/6 for $x = 1/12$. Roughly speaking, then, electroproduction of a state that cannot be photoproduced with real photons will cost about an order of magnitude in cross section relative to a state that *can* be photoproduced.

Now we seek a reference cross section for electroproduction of a *known* state with mass not too different from that of $X(1865, 0^{--})$. We first look for evidence of π^0 exchange in *photoproduction*. This will give rise to neutral states with odd C. Such a process has been seen in photoproduction of the $\omega(782, 1^{--})$ meson with polarized photons of energy 2.8, 4.7, and 9.3 GeV [35]. The photon polarization enables the isolation of unnatural parity (i.e., pion) exchange. Fitting the differential cross sections $d\sigma/dt$ at all three energies, where t

is the invariant momentum transfer, one finds for unnatural-parity exchange

$$\frac{d\sigma^U}{dt} = Ae^{bt}/E_\gamma^2 \ , \quad A = 164 \text{ nb} \ , \quad b = 7 \text{ GeV}^{-2} \ , \tag{5}$$

yielding $\sigma^U = 0.23$ nb at $E_\gamma = 10$ GeV. The first stage in observing electroproduction of $X(1865, 0^{--})$ would be to see evidence for π^0 exchange in $\omega(782)$ photoproduction.

The next step is to observe π^0 exchange in photoproduction of a $C = -$ state as close as possible in mass to the $X(1865)$. Such a state is a radial excitation ω' of the $\omega(782)$, denoted in [19] by $\omega(1650)$. As its mass is quoted as 1670 ± 30 MeV, we shall refer to it as ω' to avoid confusion with the $J = 3$ state of similar mass. If produced with a virtual photon of small Q^2 and $\nu = 10$ GeV, and with the same differential cross section as for $\omega(782)$ production, the effect of $t_{\min}$ is only suppression by a factor of 0.85. However, one can estimate (see the Appendix) using vector dominance and the known total width of ω' that a further suppression factor of ~ 0.5 is likely, leading to an overall suppression factor of about 0.4 and a net cross section of 0.1 nb.

One must then observe the pion-exchange contribution to ω' *electroproduction.* The step from photoproduction to electroproduction is a key ingredient of the CLAS12 program, and a yield of about 10^7 equivalent 10 GeV photons per second on a 30 cm long liquid hydrogen target is expected [34], corresponding to about 10^5 events per nb per 10^7 second year of exposure. Thus one should at least expect about ten thousand events of ω' electroproduction via π^0 exchange.

The final step is extrapolation to $X(1865)$ electroproduction via π^0 exchange. As mentioned, the price one has to pay for a process allowed for $Q^2 > 0$ but forbidden for $Q^2 = 0$ is roughly an order of magnitude in cross section, leading to a predicted cross section of $\mathcal{O}(10 \text{ pb})$, so a signal at CLAS12 of up to a thousand events is conceivable. A key factor signaling the electroproduction of a 0^{--} state will be the vanishing of the cross section linearly as $Q^2 \to 0$.

VI POSSIBLE VARIANT APPROACHES

The expected signal of $\mathcal{O}(10^3)$ events of $X(1865, 0^{--})$ electroproduction via π^0 exchange provides some leeway when considering possible modifications of our estimate.

- We have estimated couplings to $\rho\pi$ to be equal for ω' and $X(1865)$. A signal of $\mathcal{O}(100)$ events still remains if the latter coupling is reduced by a factor of 3.

- Regge phenomenology could have been used to estimate $X(1865)$ electroproduction. However, at small momentum transfer the exchange of an elementary pion is almost the same as the exchange of a pion trajectory (see Ref. [29]).

- Other Regge trajectories, such as a_1 and a_2, could have been considered. However, in contrast to pion exchange, where we do see evidence for X–ρ–π coupling, we cannot estimate the couplings of these other trajectories to ρ–X. Their contribution relative to pion exchange could be estimated by studying the energy dependence of X electroproduction, which is different for pion exchange and trajectories with intercept 1/2 such as a_2, and looking for evidence of the pion pole in t dependence.

- In the absence of experimental information, we cannot estimate the effect of a possible direct coupling of the X to the proton, though if it exists it is unlikely to interfere destructively with other sources of X.
- The estimate of a_2 photoproduction in Ref. [29] due to Reggeized charged pion exchange yields $\sigma(\gamma p \to a_2 n) \simeq 200$ nb at a photon energy of 10 GeV. When extrapolating this to $e^- p \to e^- X(1865) p$ electroproduction, note that (i) the pion-nucleon coupling for neutral meson photoproduction via π^0 exchange is a factor of $\sqrt{2}$ less, suppressing the rate by at least a factor of two; (ii) the $|t_{\rm min}|$ suppression factor is ~ 0.85; (iii) the vanishing of the cross section at $Q^2 = 0$ imposes at least another order of magnitude suppression. One still would expect a cross section of several nb, which is far above our less optimistic estimate of 10 pb. This tension will be resolved once the ω' photoproduction and electroproduction cross sections are measured at real or virtual photon energies around 10 GeV.

Our treatment thus may be considered as a minimal set of assumptions providing an order-of-magnitude estimate of a signal. We prefer to rely to the greatest possible extent on experimental checks and to the least degree upon theoretical calculations. The stepwise program we have suggested provides a means to such an estimate.

VII SUMMARY

We have proposed a test for the existence of an exotic isoscalar resonance dominating $D^0 \to \pi^+\pi^-\pi^0$ decays. It involves isolating neutral-pion exchange in the electroproduction process

$$e^- + p \to e^- + X(1865, J^{PC} = 0^{--}) + p \ , \tag{6}$$

with subsequent decay of $X(1865)$ into all three charge states of $\rho\pi$. It is a multi-step program well suited to an intermediate-energy accelerator such as the 12 GeV upgrade at JLAB. The steps include (i) study of $\omega(782)$ electroproduction, including isolation of the pion-exchange contribution, (ii) a similar investigation for ω', the radial excitation of $\omega(782)$ around 1670 MeV, and (iii) search for $X(1865)$, including the expected vanishing of its electroproduction cross section as $Q^2 \to 0$.

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APPENDIX

We have assumed equal differential cross sections for the pion-exchange contribution to electroproduction of $\omega(782)$ and its presumed radial excitation ω'. This requires the pion-photon coupling constants for $\omega(782)$ and ω' to be the same. We can examine the validity of this assumption using the hadronic width of ω' and vector meson dominance.

The decay $\omega(p) \to \pi^0(q)\gamma(k)$ may be described by the covariant matrix element

$$\mathcal{M} = g_{\omega\pi\gamma}\epsilon_{\mu\nu\kappa\lambda}\epsilon^{\mu}(p)\epsilon^{\nu}(k)p^{\kappa}k^{\lambda} \ , \tag{7}$$

yielding the expression

$$\Gamma(\omega \to \pi^0\gamma) = \frac{g^2_{\omega\pi\gamma}p^{*3}}{12\pi m^2_{\omega}} \ , \quad p^* \equiv \frac{M^2_{\omega} - m^2_{\pi}}{2m_{\omega}} \ , \tag{8}$$

where $p^* = 379.9$ MeV is the magnitude of the center-of-mass three-momentum of either final particle. Using values of masses, branching ratios, and widths from [19], one finds $g_{\omega\pi\gamma} = 0.544$.

Taking $g_{\omega'\pi\gamma} = g_{\omega\pi\gamma}$, and noting for $\omega' \to \pi^0\gamma$ that $p^* = 829.5$ MeV, one finds $\Gamma(\omega' \to \pi^0\gamma) = 1.61$ MeV. This value is now used to calculate $\Gamma(\omega' \to \pi^0\rho^0)$ applying vector meson dominance.

The matrix element of the vector current between the vacuum and the one-ρ-meson state may be parametrized as

$$\langle 0| V_{\mu} \left|\rho^0(p)\right\rangle = \epsilon_{\mu}(p)f_{\rho}m_{\rho} \ , \tag{9}$$

where ϵ_{μ} is the ρ polarization vector. The quantity f_{ρ} (the ρ meson decay constant) may be evaluated using the relation

$$\Gamma(\rho \to e^+e^-) = \frac{4\pi\alpha^2 f^2_{\rho}}{3m_{\rho}} = (7.04 \pm 0.06) \text{ keV} \ , \tag{10}$$

where we have neglected the electron mass and the experimental value is that quoted in [19]. The result is $f_{\rho} = (156.4 \pm 0.7)$ MeV. (A similar value is obtained from the decay $\tau \to \rho\nu$.) Now we can write

$$\Gamma(\omega' \to \pi^0\gamma) = \left(\frac{ef_{\rho}}{m_{\rho}}\right)^2 \left(\frac{p^*(\omega' \to \pi^0\gamma)}{p^*(\omega' \to \pi^0\rho)}\right)^3 \Gamma(\omega' \to \pi^0\rho^0) \ \ , \tag{11}$$

where $p^*(\omega' \to \pi^0\gamma) = 829.5$ MeV, $p^*(\omega' \to \pi^0\rho^0) = 646.3$ MeV, with the result $\Gamma(\omega' \to \pi^0\rho^0) = 203.8$ MeV, or, accounting also for decays to $\pi^{\pm}\rho^{\mp}$,

$$\Gamma(\omega' \to \pi\rho) = 611 \text{ MeV} \ . \tag{12}$$

Now, Ref. [19] lists $\Gamma_{\text{tot}}(\omega') = (315 \pm 35)$ MeV. This implies that we should take

$$g^2_{\omega'\pi^0\gamma}/g^2_{\omega\pi^0\gamma} \leq (315/611) \simeq 0.5 \ , \tag{13}$$

leading to a similar reduction of the ω' photoproduction cross section as implemented in Sec. V.

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